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NAVSTAR GPS ACCURACY WHILE SURVEYING ARRAYS OF DEEP OCEAN TRANSPONDERS

By
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Data Processing Division

December 1985

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1. SUMMARY

This paper presents the observed accuracy of the Navstar GPS Global Positioning System when used with acoustic data to geodetically locate arrays of bottom-mounted ocean transponders. Two arrays were to be located, and each was surveyed on several separate occasions. In addition to GPS with dual frequency precise P-code, the arrays were located by using Argo, Syledis, Transit satellites, and by several other tracking methods. Because the array positions have been well determined, the data is now able to reveal the absolute GPS fix error while at sea. For one survey, ground truth information from the Yuma GPS facility, 263 nautical miles (487 km) away, was used to reduce measurement bias.

This paper was approved for public release by the Naval Air Systems Command, under the title of "Navstar GPS Accuracy While Surveying at Sea." A somewhat shortened version of it, called "GPS Accuracy While Surveying Arrays of Deep Ocean Transponders," was presented at the First International Symposium on Precise Positioning With the Global Positioning System, 15-19 April 1985, at Rockville, Maryland. The full version, under the original title, was presented at the 63rd Meeting of the Range Commander's Council - Data Reduction and Computer Group, 16-20 September 1985, at Oxnard, California.

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2. INTRODUCTION

Arrays of bottom-mounted ocean transponders can be used for various applications such as in the oil industry. A ship would activate the transponders so that they echo back acoustic replies. By using appropriate triangulation methods, the ship is then able to locate and track itself. Before an array can be used, its transponders must be geodetically surveyed as accurately as possible. A survey ship must move back and forth above the array while it records both its own geodetic ship fixes and also the in-water acoustic transit times between its pinger and the transponders. The relative positions of the transponders within the array are solved for by using the acoustic data by itself. The centroid of the array and its orientation to north are solved for by using the geodetic ship fixes together with the acoustic data.

Two arrays of transponders were surveyed. Array A is a calibration array located 35 nautical miles (nmi) southwest of Point Mugu, California, between Santa Cruz Island and San Nicolas Island in waters 1900 meters deep. It was surveyed on three different occasions, using Navstar GPS as well as six other tracking methods. Array B is located elsewhere, and it was surveyed on two different occasions, once with GPS precise P-code. Array A is of more interest for this discussion because it was surveyed more often with more methods, and thus its geodetic location is well known. Also, Array A is 263 nmi (487 km) from the Inverted Range GPS facility at Yuma, Arizona, which allows one to attempt differential GPS methods by using Yuma's ground truth results.

The location of Array A is quite well determined, based on the first two surveys: Its transponders have a one-sigma horizontal uncertainly of only 0.24 meter relatively, a depth uncertainty of 0.4 meter, a geodetic uncertainty of the array centroid of only 1.5 to 3 meters, and an orientation uncertainty to north of 0.008°. Now acoustic self-tracking will be used with Array A for the third survey, and by comparing the corresponding GPS fixes with it, one can learn how well GPS has performed. Error propagation shows the noise in this acoustic self-tracking to be about 1.0 meter; the bias is the above amount of 1.5 to 3 meters. Thus, acoustic self-track can yield "true" ship positions which are a standard of comparison against which ship fixes from GPS, etc., can be compared.

Usually, it is quite difficult to observe the error in GPS while at sea. One can try to use some geodetic tracking method such as Argo or Miniranger for comparisons, but these systems have their own biases and noise which tend to obscure the GPS error. Acoustic self-tracking with a well surveyed transponder array offers a unique opportunity. Because of the smoothness of acoustic self-tracking, one now has a standard of comparison at sea which is an order of magnitude better than what is being observed.

3. SURVEYING WITH THE VARIOUS TRACKING SYSTEMS

The GPS data was obtained by using a Texas Instruments TI-4100 user set, and it was unaided and independent from the other systems aboard the ship. Precise P-code was used, and only fixes from four satellites were used. The antenna was mounted near the rear of the ship, 18.0 meters behind the pinger.

Thus a knowledge of the ship's heading is needed to transform fixes from the antenna to the pinger.

In addition to GPS, the arrays were surveyed using Argo, Syledis, the Extended Area Test System (EATS), precision tracking radars, Loran-C, and Transit satellites. In figure 1 are shown various array centroid estimates for Array A. The table which follows shows the resulting centroid error and orientation error when each system was used. Also listed in the table are statistics obtained by comparing each system's ship fixes with acoustic self-track fixes. In figures 2 and 3 are shown the scatter plots of ship fix error for some of these cases. (X is positive east, and Y is positive north.)

Argo is a radio navigation phase-measuring system which can detect changes in distance back to its several ground stations. It must be initialized by using an independent knowledge of position, and this was accomplished by using Syledis fixes when closer to shore. If Argo is carefully calibrated by methods such as baseline crossing tests, then it can provide highly repeatable results. It uses groundwaves which can reach relatively far before skywave interference renders the fixes unuseable. The main limitation of Argo is the uncertainty in its radio propagation velocity over long distances.

Syledis is a radio navigation system which can directly measure distances back to its ground stations, and it does not have to be initialized or calibrated in the field. It is accurate closer to shore where line-of-sight transmission can be used, although its accuracy can often be maintained over the horizon where radio diffraction and scattering modes are needed. As with Argo, its accuracy is limited by uncertainty in the radio propagation velocity.

EATS is an acronym for Extended Area Test System, which is a radio-frequency triangulation system in use by the Pacific Missile Test Center. Transponders are located at ground stations along the coast and on the offshore islands. Other transponders are placed on aircraft or ships to be tracked, and range measurements between transponders are then recorded.

Precision tracking radars at Point Mugu and at San Nicolas Island were used for Array A. Only one radar was used at a time.

Loran-C was used, but the receiver was not operating properly. The bias in the fixes would repeatedly shift from one value to another throughout each survey. Usually, Loran-C results can be expected to be somewhat noisy with a bias of perhaps a hundred meters or so.

Fixes from Transit satellites were used, and they were processed using both the broadcast ephemeris and the precise ephemeris. Only satellite passes which met customary quality criteria were used, and there was some effort to balance the number of northbound and southbound passes, and the number of eastward and westward passes. When using Transit fixes on land, one can locate oneself quite accurately if enough passes are used, since Transit fixes are noisy but are generally unbiased. However, at sea the satellite fix calculations are sensitive to uncertainties in the ship's velocity. One needs to know the speed and heading of the ship during the

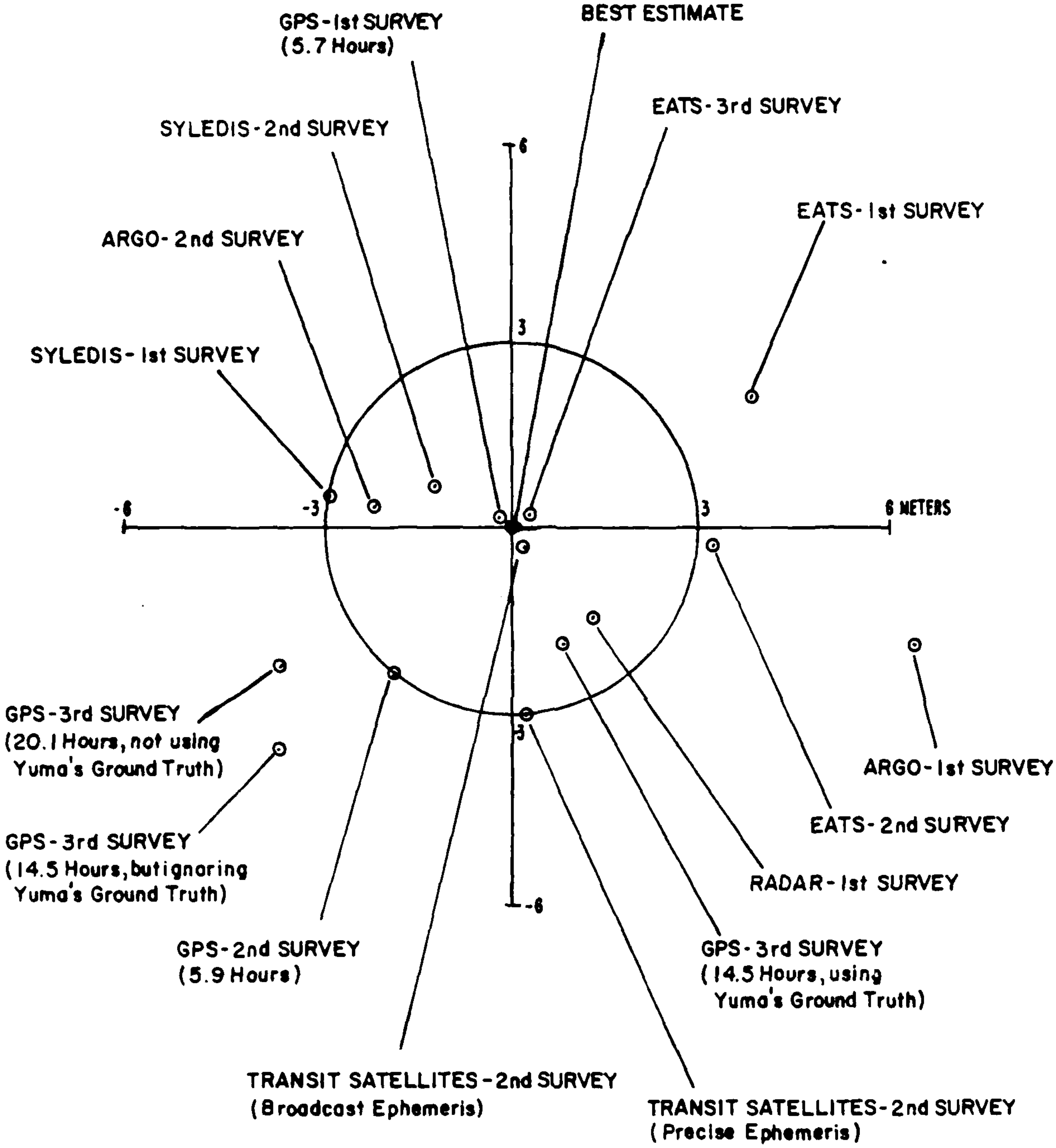

FIGURE 1. VARIOUS ESTIMATES OF THE CENTROID OF ARRAY A.

SURVEY RESULTS, USING VARIOUS TRACKING METHODS

ARRAY, SURVEY	TRACKING SOURCE	DISTRIBUTION OF SHIP FIX ERROR					LOCATING THE ARRAY		
		NO. OF FIXES	X,Y MEAN (METERS)		X,Y STD.DEV. (METERS)		CENTROID X,Y ERROR		ROTATION ERROR
A-1	ARGO	4750	5.2	-1.8	8.8	6.7	8.8	-1.8	+0.001
2	ARGO	6265	-2.1	0.6	6.1	3.4	-2.1	0.3	-0.002
1	SYLEDIS	6442	-4.0	0.3	18.6	11.9	-2.9	0.4	+0.004
2	SYLEDIS	5463	-1.2	0.6	11.6	5.5	-1.2	0.6	-0.011
1	EATS	5492	5.5	2.1	49.1	11.9	3.9	2.0	-0.004
2	EATS	6547	3.4	-0.3	24.1	10.4	3.3	-0.3	+0.012
3	EATS	8081	-1.2	0.0	22.3	6.4	0.3	0.2	+0.005
1	LORAN-C (EQUIP. PROBLEMS)	4720	-49.1	-243.2	93.9	275.8	4.9	-65.4	+0.184
2	LORAN-C (EQUIP. PROBLEMS)	3873	50.0	-247.2	131.7	360.3	13.9	116.1	+0.056
3	LORAN-C (EQUIP. PROBLEMS)	9482	-77.1	-134.1	100.0	221.3	-42.0	-37.9	+0.022
1	RADAR	544	11.3	-10.7	54.9	47.2	1.3	-1.4	+0.033
2	RADAR	885	13.1	14.3	13.1	11.0	13.5	14.3	-0.014
2	TRANSIT SATELLITES, BROADCAST EPHEMERIS	41	---	---	37.5	40.2	0.2	-0.4	+0.073
2	TRANSIT SATELLITES, PRECISE EPHEMERIS	41	---	---	32.3	37.5	0.3	-3.0	+0.012
3	TRANSIT SATELLITES, BROADCAST EPHEMERIS	39	---	---	63.3	66.3	-11.2	26.4	-0.202
1	GPS (5.7 HOURS OVER FOUR DAYS)	301	0.3	1.5	22.3	10.1	-0.1	0.2	+0.025
2	GPS (5.9 HOURS OVER TWO DAYS)	179	-0.6	-4.9	10.7	4.9	-1.8	-2.4	-0.014
3	GPS (20.1 HOURS OVER SIX DAYS)	1118	-3.7	-3.4	10.7	6.7	-3.6	-2.3	+0.004
3	GPS (14.5 HRS WITH YUMA GROUND TRUTH)	821	0.0	-3.0	7.6	5.2	0.8	-1.9	+0.008
3	GPS (14.5 HRS, BUT IGNORING YUMA)	821	-3.7	-4.9	9.8	5.2	-3.7	-3.6	+0.008
B-1	ARGO	4269	-0.3	-8.8	11.9	9.1	1.7	-9.4	+0.000
2	ARGO	3466	3.7	-3.7	11.0	10.7	4.4	-3.4	-0.001
2	SYLEDIS	4480	-0.6	-1.5	11.3	7.0	-0.3	-0.3	+0.002
2	LORAN-C (EQUIP. PROBLEMS)	11018	---	---	24.1	27.7	---	---	+0.030
1	TRANSIT SATELLITES, BROADCAST EPHEMERIS	37	---	---	---	---	0.8	9.8	-0.075
2	TRANSIT SATELLITES, BROADCAST EPHEMERIS	34	---	---	67.7	34.7	-9.0	11.7	-0.125
2	TRANSIT SATELLITES, PRECISE EPHEMERIS	21	---	---	81.4	56.7	2.2	11.8	-0.028
[illegible]	TRANSIT, USING AN ALTERNATE ALGORITHM						1.1	4.7	-0.003
1	GPS MANPACK USING C/A CODE	340	22.6	-4.9	58.5	28.0	2.4	6.1	-0.143
2	GPS (19.2 HOURS OVER NINE DAYS)	1105	-3.0	0.6	10.4	8.2	-2.5	0.6	-0.007

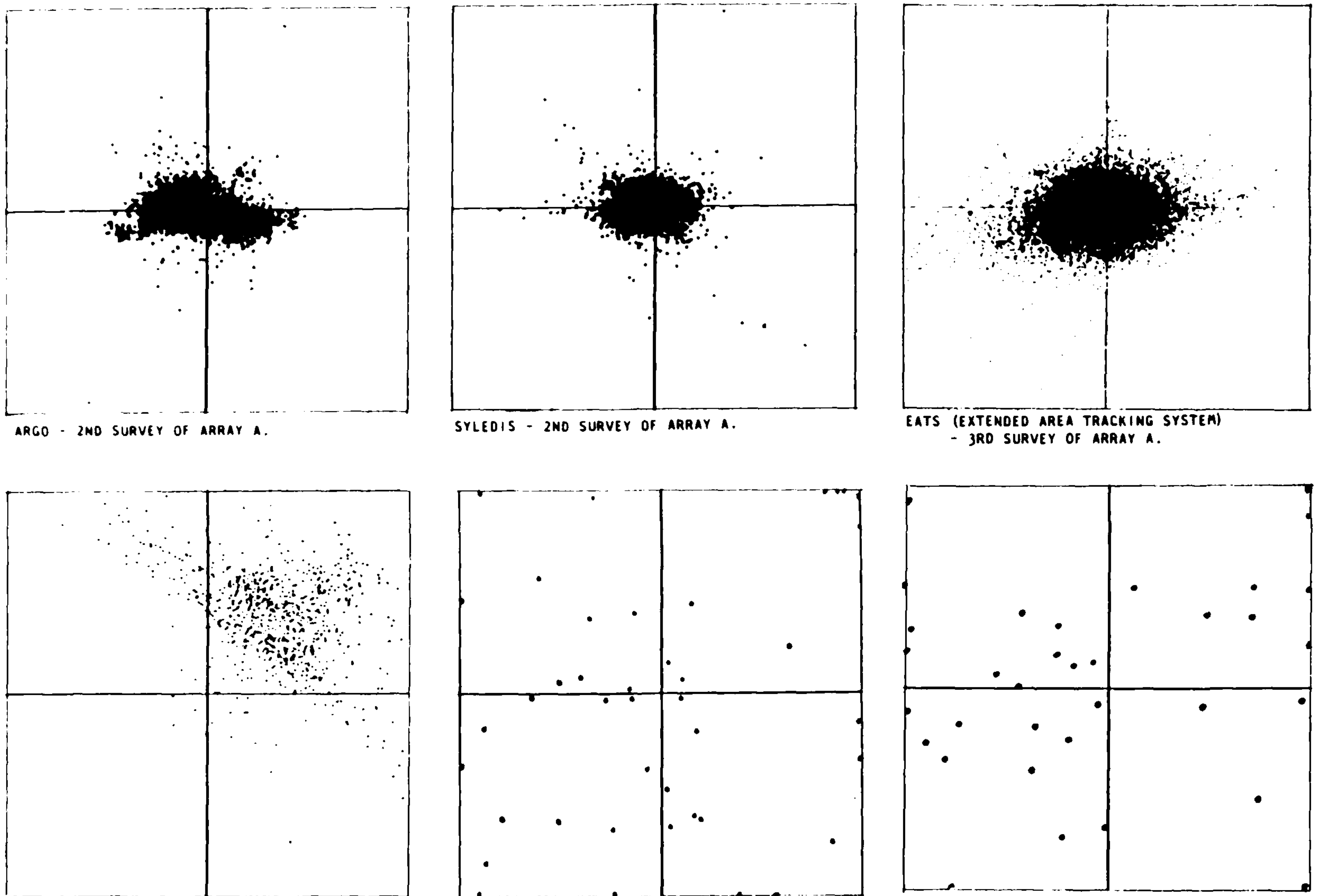

FIGURE 2. SHIP FIX ERROR FOR VARIOUS TRACKING SYSTEMS. (PLOT LIMITS ARE $\pm$ 40 METERS.)

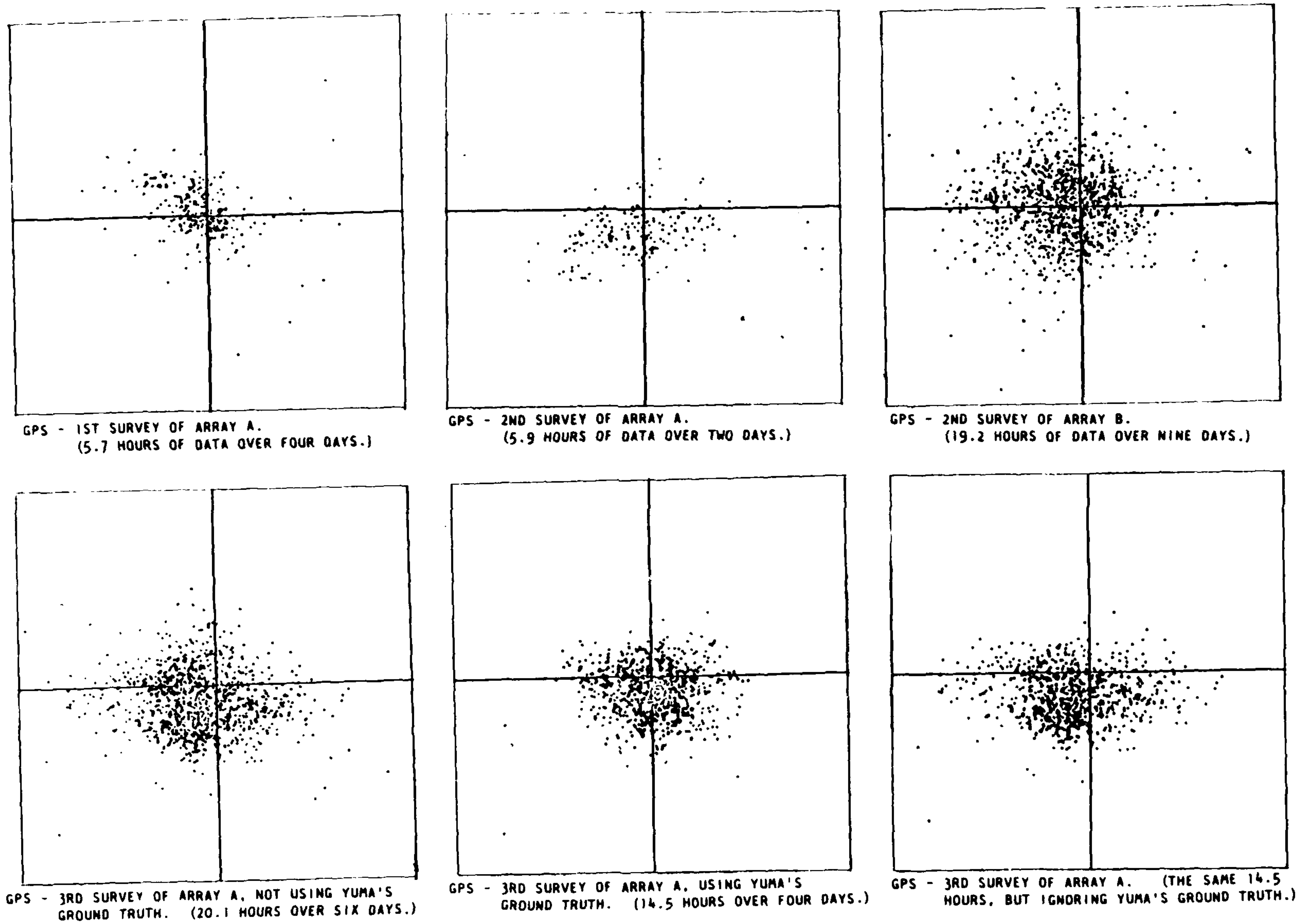

FIGURE 3. SHIP FIX ERROR OBSERVED FOR GPS. (PLOT LIMITS ARE ± 40 METERS.)

satellite data collection in order to properly calculate the fix. Experience with these and other surveys has shown that the resulting centroid estimates are not unbiased. The ship did not have inertial navigation, and perhaps this would have helped during the data collection. But as often as not, the averaging of small numbers of Transit fixes led to relatively large array centroid errors.

For the first and second surveys of Array A, four-satellite GPS fixes were collected for only 5.7 hours over four days, and 5.9 hours over two days, respectively. . Even with such small amounts of data, they yielded adequate centroid estimates. For the third survey of Array A, there was a total of 20.1 hours of good data collected over six consecutive days. For 14.5 hours of this data, Yuma's ground truth information was available. For the second survey of Array B, there was 19.2 hours of good data collected over nine days.

4. THE OBSERVED NOISE IN GPS FIXES

It is unfortunate that the GPS antenna had been placed so far back of the ship's pinger, because then one needs to know the ship's orientation in order to transform fixes to the pinger's location. As will be seen, much of the noise observed in the GPS fixes may actually be caused by uncertainties in the ship's heading rather than in the GPS fixes themselves. However, the only places close to the pinger were high on masts; the rocking motion of the ship would then be magnified, and the apparent high antenna accelerations would keep the TI-4100's Kalman filter from tracking properly.

For the third survey of Array A, the ship's gyrocompass was unable to supply headings. As a substitute, the ship's direction of motion was obtained by using the velocity components output by the ship computer's Kalman filter. Once each minute, acoustic self-track fixes were input to this Kalman filter; with such a slow data rate, the filter's velocity estimates were too smoothed and not responsive enough, and the resulting direction of motion lagged behind the true direction. (The "true" direction was calculated later by fitting each three consecutive acoustic self-track fixes with a quadratic curve and by taking the derivative of the curve at the middle fix.)

When the ship is under power, the direction of motion (i.e., course-made-good) is a reasonable estimate of heading. But when the ship is dead in the water and drifting with the wind and current, one cannot validly estimate the heading. Because of this, 7.4 hours of good GPS fixes had to be discarded, leaving 20.1 hours of data to work with.

It was found that the above-mentioned uncertainties in heading were directly causing much noise in the observed GPS fixes. The GPS-derived velocity outputs from the TI-4100 were then used instead, and the resulting heading was found to be superior. The TI-4100's Kalman filter was updated every three seconds, and so it was more responsive and its results agreed better with the "true" headings. With the heading estimates based on GPS, the apparent noise in the GPS fixes was greatly reduced.

Figure 4 shows plots of GPS fix noise for days 262 and 263 for the third survey of Array A (using GPS-derived heading). On day 262, the ship is

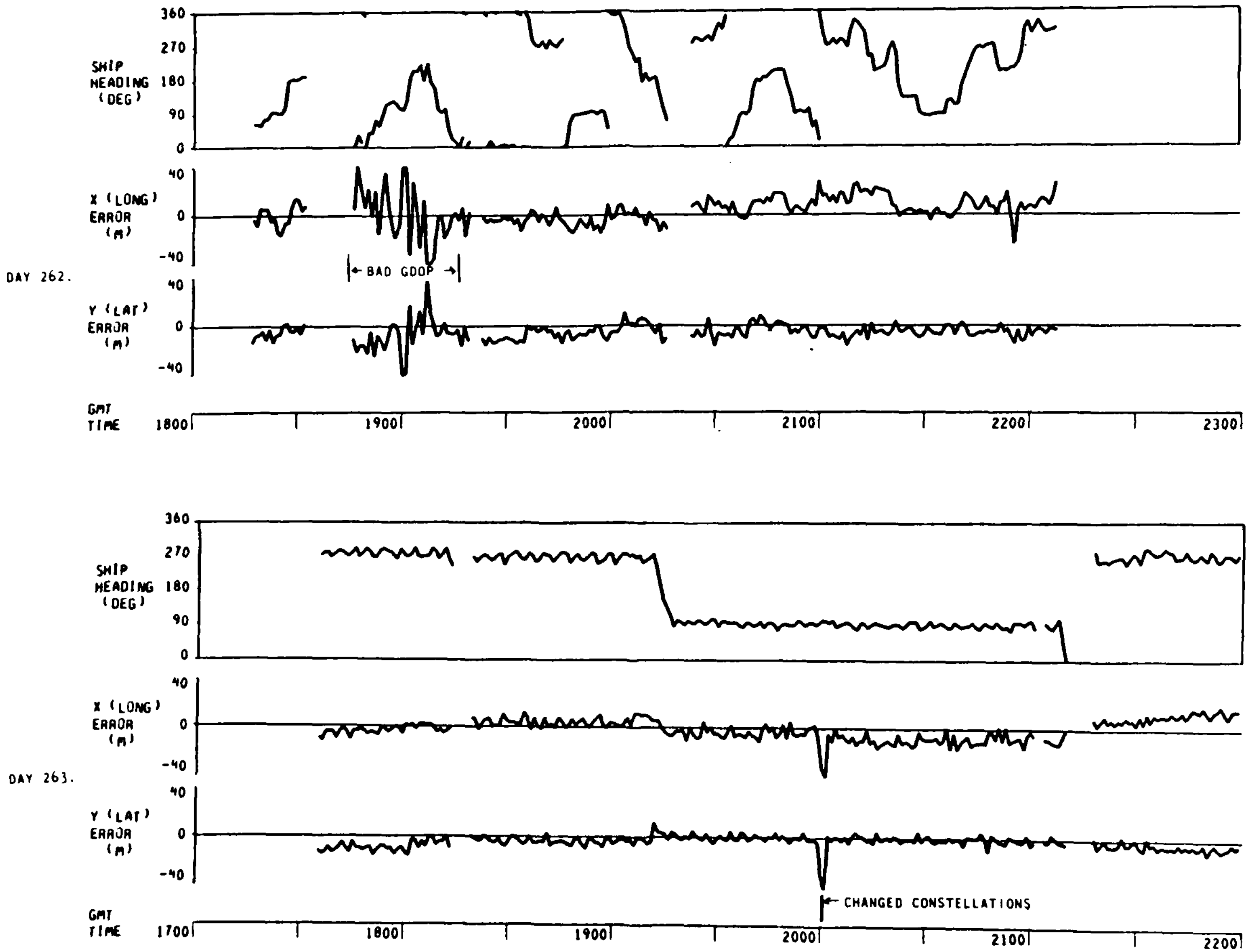

FIGURE 4. GPS FIX NOISE, AS RELATED TO CHANGES IN SHIP HEADING. (FOR TWO DAYS.)

turning often and the result is noisier fixes. On day 263, the ship is making periodic heading corrections so as to maintain a course due east or due west, and the resulting fix noise is less. Because the ship is moving east or west, the uncertainty in heading will show up mainly as Y error. Because figure 4 shows the X error to be about as large as the Y error, one can conclude that the plots are showing actual noise from the TI-4100 and not just the results of heading uncertainty. Much of the noise is probably caused by the ship's pitch, roll, and yaw being transformed into GPS antenna movement.

5. COMPARING OBSERVED GPS FIX ERROR WITH YUMA'S GROUND TRUTH

Figures 5 and 6 show plots of GPS fix error and Yuma's ground truth for days 262 and 263. Also shown are the geometric dilution of precision (GDOP), and the times the satellites were uploaded with ephemeris and clock corrections. At the U.S. Army Yuma Proving Grounds, the U.S. Air Force Space Division operates a sophisticated GPS set at a well-surveyed location and records the observed fix biases each day. The Yuma set is 263 nmi away, and so it sees almost the same biases in its fixes as does the ship. The satellite clock bias is the same for both locations. The satellite ephemeris error seen from the two sites is almost the same: At worst, the radial directions from the satellite to two sites 250 nmi apart are only 1.35° apart. When a satellite is close to the horizon, each set may correct somewhat differently for tropospheric refraction, and this might cause a small disagreement in bias. (For a site 250 nmi away, the horizon and zenith tilt by about 4.16°.) Also, two different types of sets may process their data in different ways, causing some difference. But the main reason why two sites 250 nmi apart may experience bias differences is differences in the ionosphere. With P-code, most of the effects of the ionosphere have been removed. However, a residual uncompensated error remains. If the ionosphere is roughly homogeneous between the two sites and the satellites, then there will be a high correlation in observed biases. But if the ionosphere is "stronger" over one site than over the other, then the correlation will be less.

Yuma's ground truth was available for four of the six days, and figures 5 and 6 are typical of these four days. Notice that there is a definite correlation between the GPS fixes and Yuma's ground truth, but that at times they disagree. On some days, there seems to be a northward bias in the fixes relative to Yuma and this can also be seen in figure 7; this is probably due to chance however. Notice that the TI-4100 lags by up to half an hour in its altitude solutions after some uploads and constellation changes cause the altitude to change sharply.

On the average, the use of Yuma's ground truth removes much of the bias and thus yields better survey results. Notice the two scatter plots in figure 3 which show the same 14.5 hours of fixes before and after ground truth has been used. The use of ground truth has made the scatter pattern become more compact, and it has reduced the error in the array centroid estimate from 5.16 meters to 2.06 meters.

A separate test was made on land at a distance of 244 nmi (452 km) from Yuma, to see how much correlation there would be. In August 1983, a static test was performed at Point Mugu, in which a High Dynamics User Equipment set

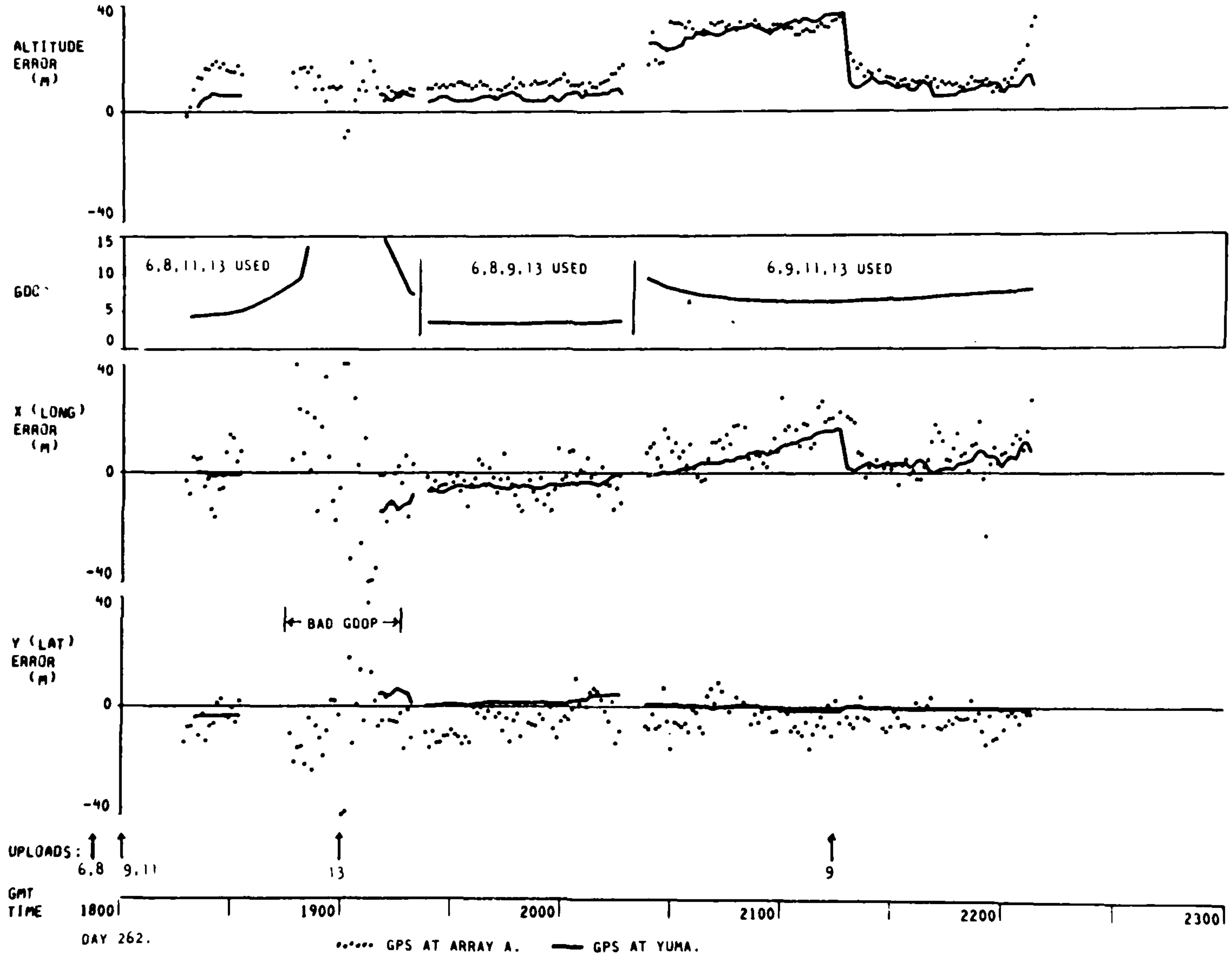

FIGURE 5. GPS FIX ERROR COMPARED WITH YUMA'S GROUND TRUTH.

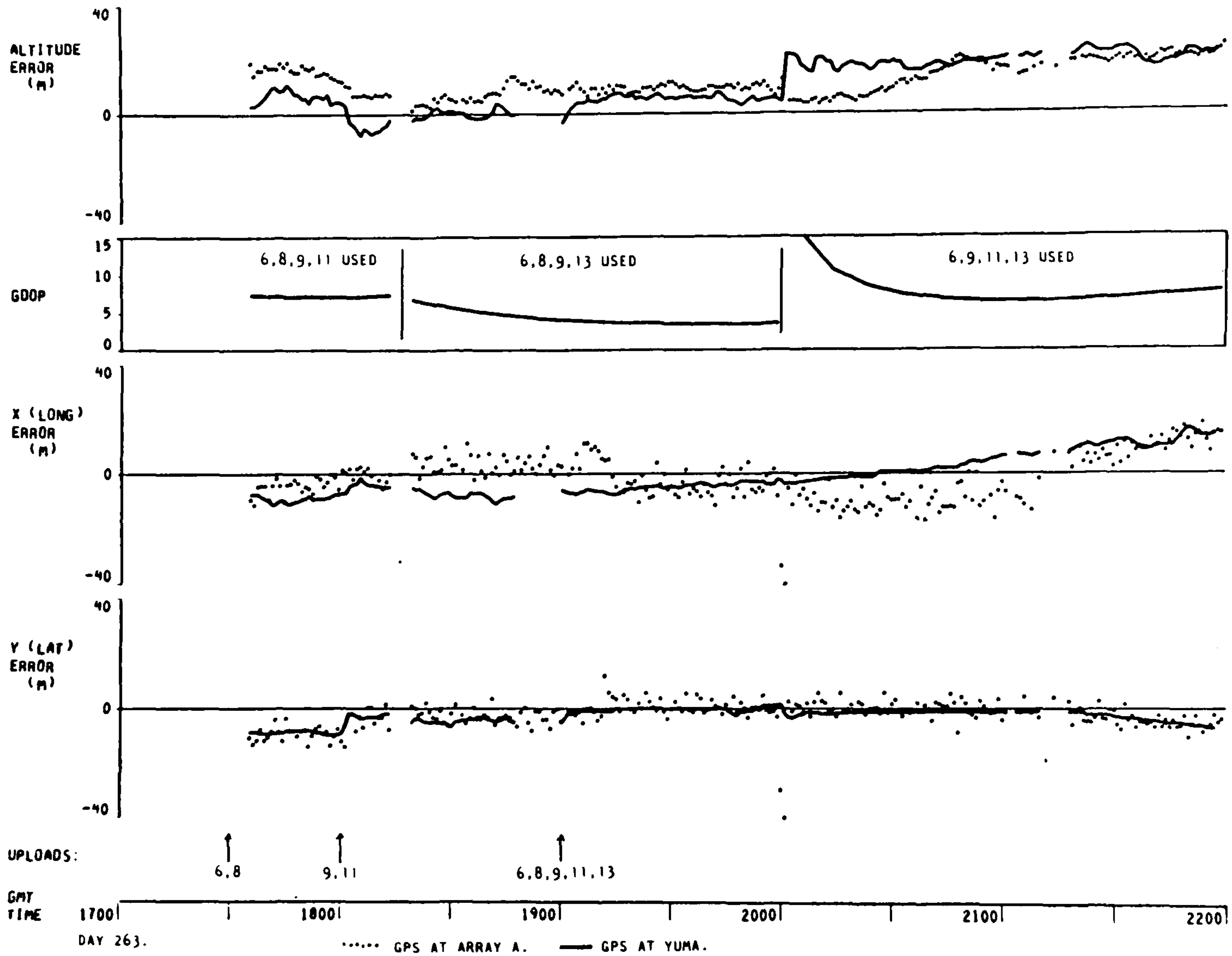

FIGURE 6. GPS FIX ERROR COMPARED WITH YUMA'S GROUND TRUTH.

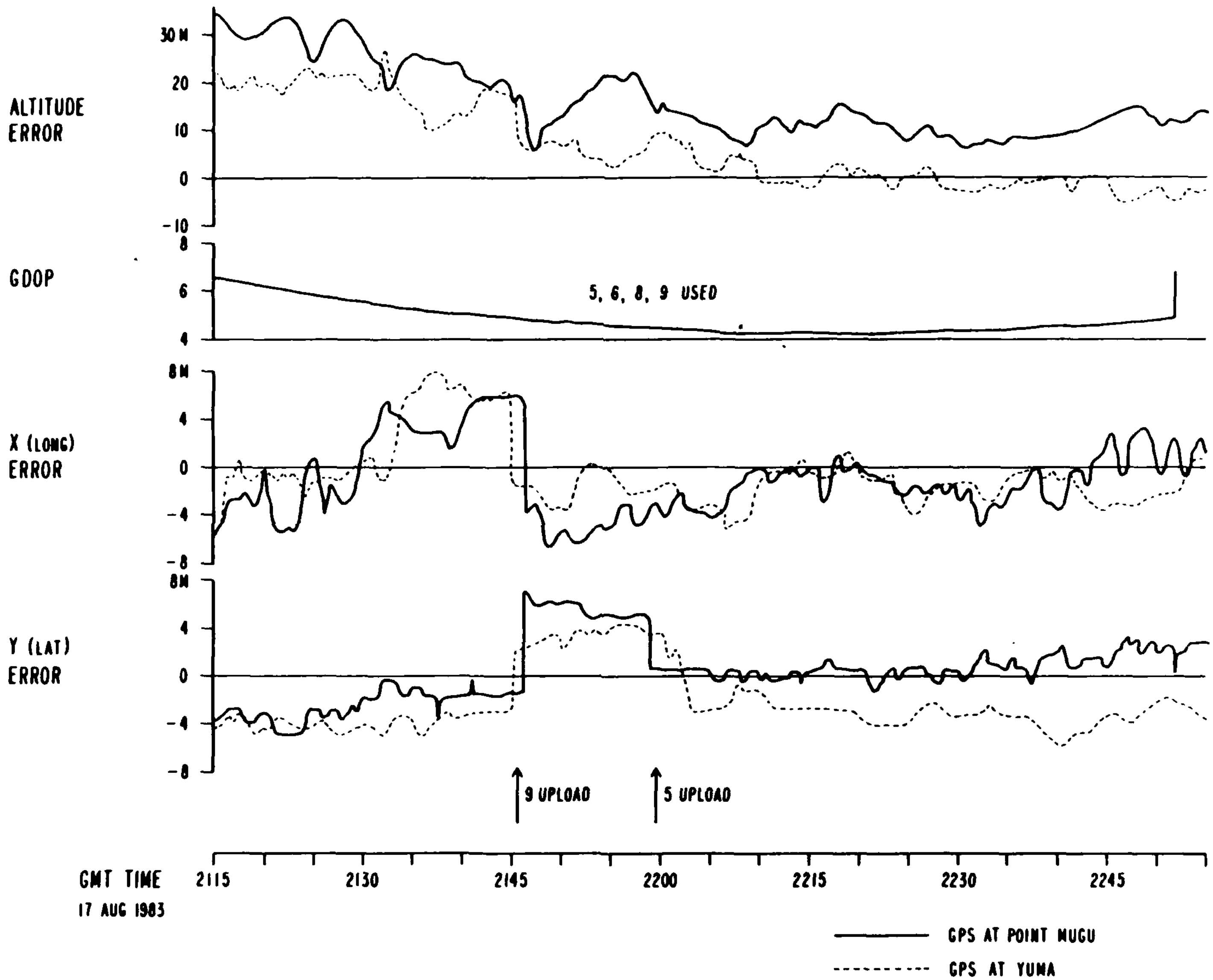

FIGURE 7. GPS FIX ERROR ON LAND, COMPARED WITH YUMA'S GROUND TRUTH.

mounted in a UC-880 aircraft was parked over a surveyed point. A total of 1.7 hours of P-code data was recorded. The results are plotted in figure 7, along with the results as seen at Yuma. Notice that the results are closely correlated, but that there are offsets in the biases.

6. CONCLUSION

Navstar GPS is the ideal system for surveying transponder arrays at sea. Only GPS can avoid the weaknesses of Transit satellites and of radio navigation systems such as Argo and Syledis. The main weakness of Transit satellites is their sensitivity to uncertainties in ship velocity during a doppler interval; GPS does not have this problem because it uses triangulation instead. The main weakness of Argo is that the long over-water radio paths from ground stations suffer from an uncertainty in the radio propagation velocity; GPS does not have this problem because its signals come from above. With a second GPS receiver at a surveyed point on land, the biases in GPS fixes can be greatly reduced, resulting in survey accuracy as well as precision.

From these tests, one can see that when P-code GPS data was recorded at a distance of 263 nmi from Yuma, the use of Yuma's ground truth has greatly reduced but not eliminated measurement bias. On other occasions, ionospheric conditions may reduce this correlation, however. Regardless of this, if GPS data is averaged over enough days, the result should be a survey of acceptable accuracy.

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